Case Studies – Automotive Sector

Life Cycle of CO_2-Emissions from Electric Vehicles and Gasoline Vehicles Utilizing a Process-Relational Model

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Abstract. This article aims at estimating life cycle CO_2 emissions from electric vehicles (EV) and gasoline vehicles (GV), although the estimation in this study is not an LCA according to ISO14040s. For this purpose, a mathematical tool called the Process-relational model was developed. The Process-relational model is used for establishing life cycle inventories. The model has a structure which improved the principle of input-output analysis in econometrics that only one product is generated by one process. This model enabled us to overcome difficulties of LCA in retracing complicated repercussions among production systems.
Then, life cycle CO_2 emissions from electric vehicles (EV) and gasoline vehicles (GV) were estimated with this model. Estimated results indicated that the manufacture and driving of EV resulted in less CO_2 emissions than those of GV. However, the difference between EV and GV dramatically changed depending on traffic situations. Namely, the difference became larger as the average velocity of the vehicles became lower. We also compared CO_2 emission from manufacturing EV with that from driving EV. The share of manufacture was shown to increase in total CO_2 emissions as the average velocity of the EV became higher.
In conclusion, we clarified the direction of research and development of EV and GV for reducing the life cycle CO_2.

Keywords: CO_2 emissions; electric vehicles; gasoline vehicles; input-output table; life cycle inventories; life cycle methodologies; manufacturing; drivingmarginal allocation; Process-relational model

Introduction

This article aims at estimating life cycle CO_2 emissions from electric vehicles (EV) and gasoline vehicles (GV) utilizing the Process-relational model. This study is not an LCA according to ISO14040s.

Although there have been many assessments concerning EIO-LCA [1,3,7,10], this analysis has followed the differences from previous studies:

- In general LCA, they have to retrace one process after another to sum up all inputs and outputs resulting from the evaluated systems. This work to retrace complicated repercussions among related processes was improved by extending the principle of input-output analysis.
- The principle of marginal allocation was proposed to be able to partition input and output flows of a unit process, even if a system includes multiple production or emissions. The mathematical framework for life cycle assessment is designated the Process-relational model [2].
- Concerning the data in EIO-LCA, the environmental database developed by Yoshioka et al. [3,12] is utilized as a source of the matrices **A** and **E**. This database is established based on a Japanese input-output table from 1990, industrial statistics, and other energy statistics. Values in matrix A are determined by average inputs in each corresponding process of 405 items in Japan. In matrix E, the data covers intensities of energy consumption and CO_2 emission from each process of the 405 items in the input-output table. Hence, the database is comprehensive and also statistically reliable [3,12].

There are also many assessments concerning the LCA of EV and GV [1,6]. However, this analysis has demonstrated the following differences from previous studies:

- Actual driving modes measured in Tokyo were adopted for analyzing the performances of EV and GV, in addition to vehicles driving at constant velocities.
- Life cycle CO_2 emissions of EV with lithium ion batteries were assessed as well as those functioning with lead storage batteries.
- We also analyzed the share of manufacturing vehicles in life cycle CO_2 emissions in various driving modes.
- This analysis implied the directions of research and development for EV and GV to reduce life cycle CO_2 emissions.

1 Life Cycle Assessment Utilizing Process-Relational Model

1.1 Basic concept of Process-relational Model

Bottom-up method is usually adopted to develop life cycle inventories of investigated systems. In this method, inputs and outputs are listed in a table for each process, taking the relationships among the processes into consideration. Hence, there are difficulties in retracing the complicated repercus-

sions among the systems. On the other hand, input-output analysis [3] in econometrics is useful to reflect the complicated repercussions into life cycle inventories. We therefore apply input-output analysis to develop life cycle inventories of EV and GV.

The following is the estimation process to apply input-output analysis in this study. In input-output analysis, all necessary inputs for a process, x_i, are usually expressed in Equation (1).

$$x_j a_j = x_j \begin{pmatrix} a_{1j} \\ \vdots \\ a_{ij} \\ \vdots \\ a_{nj} \end{pmatrix} \tag{1}$$

Then, all necessary inputs for all processes from x_1 to x_n are expressed in Equation (2).

$$\sum_{j=1}^{n} x_j a_j = \begin{pmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ a_{21} & \vdots & a_{2j} & \vdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{n1} & & a_{nj} & & a_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_j \\ \vdots \\ x_n \end{pmatrix} = Ax \tag{2}$$

The following condition of balance between supply and demand is obtained from Equation (2), assuming f as a vector of final demand.

$$\mathbf{x} = \mathbf{Ax} + \mathbf{f} \tag{3}$$

$$\mathbf{x} = (\mathbf{I} + \mathbf{A} + \mathbf{A}^2 + \mathbf{A}^3 + \cdots + \mathbf{A}^n + \cdots)\mathbf{f} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{f} \tag{4}$$

Necessary inputs are determined from Equation (4), taking all possible repercussions among related processes into consideration. Although life cycle inventories on resource consumption are acquired from Equation (4), environmental emissions are not included in it. In input-output analysis, they usually adopt the principle of one process-one product, in which only one product is generated from a single process. So as to include environmental emissions in our life cycle inventories, it is indispensable to modify this principle so that multiple kinds of products or emissions can be generated from a single process. For this purpose, **Ex** is defined to be products or emissions as an output from **x** as shown in Equation (5).

$$y = Ex = \sum_{j=1}^{n} e_j x_j = \begin{pmatrix} e_{11} & \cdots & e_{1j} & \cdots & e_{1n} \\ e_{21} & \vdots & e_{2j} & \vdots & e_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e_{n1} & \cdots & e_{nj} & \cdots & e_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ \vdots \\ x_j \\ \vdots \\ x_n \end{pmatrix} \tag{5}$$

Namely, the vector **x** represents processes, while **Ax** and **Ex** represent products or emissions as an input to and as an output from the processes **x**, respectively. Thus, they can include multiple products or emissions such as CO_2, NO_X, SO_X, and so on.

The following equations are obtained by defining E–A as B_0.

$$\mathbf{x} = \mathbf{B}_0^{-1}\mathbf{f} \tag{6}$$

From equation (5) and (6), the following equation holds.

$$\mathbf{y} = \mathbf{Ex} = \mathbf{EB}_0^{-1}\mathbf{f} \tag{7}$$

Then Equation (8) is obtained by defining E_{ij} and BI_{ij} as the ij elements of the matrix E and B_0^{-1}, respectively.

$$\frac{\partial y_k}{\partial f_j} = \sum_{i=1}^{n} \left(E_{ki} \times BI_{ij} \right) \tag{8}$$

Based on Equation (8), we can allocate life cycle resource consumption or emissions of the section **k** per unit of the demand j, even if a system includes multiple production or emissions. This allocation principle is defined as a marginal allocation. At the same time, this mathematical framework for life cycle assessment is designated as the Process-relational model [2].

1.2 Boundary condition of Process-relational model for the case study GV vs. EV

LCI should take all kinds of emissions into consideration. These inventories often include toxic trace elements such as dioxins, heavy metals and so on, as well as global environmental emissions. However, this study focuses on global environmental emissions such as greenhouse gases or energy consumption. All these emissions will be dealt with in our future work.

1.3 Application of the Process-relational model in this analysis

Life cycle inventories on EV and GV are generally classified into manufacturing, driving, and treatment of End-of-Life of vehicles. This paper aims at quantifying life cycle inventories in manufacturing and driving to compare LC-CO_2 of EV with that of GV. LCI of scrapping and recycling EV and GV will also be a future work, although we have not yet acquired the reliable data on these activities.

As far as driving vehicles are concerned, electric power and gasoline consumption are estimated utilizing simulation models described in chapter three. We input the direct consumption of electric power and gasoline into the corresponding items of f in Equation (7), so that life cycle inventories of EV and GV are generated in the Process-relational model.

Concerning the manufacturing of these vehicles, we input all necessary component parts and inputs to manufacture EV and GV into the corresponding items in f so as to generate the life cycle inventories. The environmental database developed by Yoshioka et al. [3,12] is utilized as a source of the matrices A and E as described in 2.3. As a numerical

example of this model, the CO_2/kWh of electricity and the CO_2 per liter of gasoline are estimated to be 0.423 kg-CO_2/kWh and 2.85 kg-CO_2/l, respectively.

2 Estimation of Energy Consumption in Driving EV and GV

In this chapter, energy consumption in driving EV and GV is estimated. [4]. At first, the force is estimated to drive EV and GV, which is a sum of the force generated from rolling friction, air resistance and acceleration. Next, the velocity of EV and GV is multiplied by the force so that we are able to estimate the power needed to drive the vehicles. Then the energy consumption rate is estimated, taking characteristics of motors and engines into consideration. At last, we integrate the energy consumption rate as being the total energy consumption during the whole evaluation period.

2.1 Power to drive EV and GV

Rolling friction is expressed in Equation (9),where R_{roll} is rolling friction, μ_r is a coefficient of rolling friction, W is the total weight of EV or GV, and g is a gravitational constant.

$$R_{roll} = \mu_r W g \tag{9}$$

Air resistance is expressed in Equation (10), where R_{air} is air resistance, C_D is a coefficient of air resistance, ρ is air density, A is an equivalent area to evaluate air resistance and v is a velocity of EV or GV.

$$R_{air} = C_D \frac{\rho}{2} A v^2 \tag{10}$$

The force to accelerate EV or GV is expressed in Equation (11), where α is acceleration, ψ is an equivalent coefficient to increase the weight of the vehicles by rotating a motor or an engine.

$$R\alpha = \psi W \alpha \tag{11}$$

Thus, total force is the sum of R_{roll}, R_{air} and R_a as expressed in Equation (12).

$$R = Rroll + Rair + R\alpha = \mu_r W g + C_D \frac{\rho}{2} A v^2 + \varphi W \alpha \tag{12}$$

In summary, power to drive automobile, Ne, is expressed in Equation (13), in which the efficiency of transmitting power is η_t.

$$Ne = \frac{Rv}{\eta_t} \tag{13}$$

2.2 Specific characteristics of EV and GV

Table 1 shows the performances of motors and engines which are installed in EV and GV. As far as EV is concerned, one motor is implemented to drive the rear wheels.

Table 2 shows common characteristics for EV and GV. These variables are assumed based on the corresponding data for a typical passenger car, M, sold by Japanese Representative Company, T, the displacement of which is 2000cc [4].

Table 1: Performances of engines and motors

	GV	EV Lead storage battery	EV Lithium ion battery
Maximum Output (kW)	100	96.0	104
Displacement (cc)	2000	–	–

Table 2: Common characteristics for EV and GV

	GV and EV
Equivalent area to evaluate air resistance (m^2)	1.98
Coefficient of air resistance	0.34
Coefficient of rolling friction	0.01
Equivalent radius of tire (m)	0.292
Efficiency of transmitting power	0.90

The total weight of this automobile is adopted as the weight of GV. As far as EV is concerned, total weight is estimated, assuming that the batteries, the motor and other control devices are substituted for the engine and the gasoline tank. As a result, the weight of GV is assumed to be 1369 kg. On the other hand, the weights of EV with lead storage or lithium ion batteries are estimated to be 1849 kg or 1717 kg, respectively.

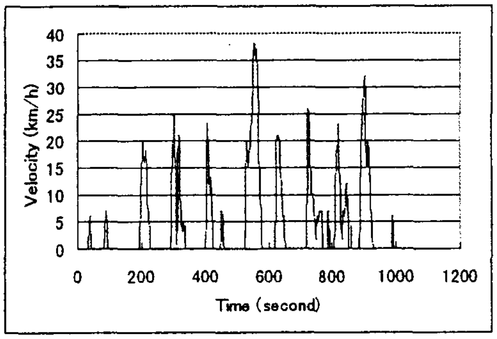
Specific characteristics of motors and batteries are shown in Table 3. Simulators of EV and GV are developed based on this data and detailed characteristics of engines, motors and batteries [4]. In estimating energy consumption to drive EV and GV, we also assumed that two people, whose weights are both fifty-five kilograms, are on these vehicles.

Table 3: Specific characteristics for EV

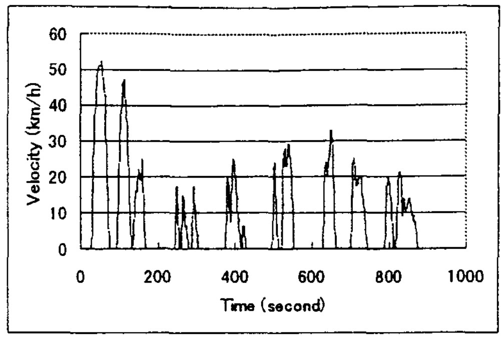
	Lead storage battery	Lithium ion battery
Weight of batteries (kg)	480	348
Output density (W/kg)	200	300
Maximum output of batteries (kW)	96.0	104
Energy density (Wh/kg)	37.5	100
Efficiency of charge and discharge (%)	80.0	95.5
Specific output of motor (kW)	80	80
Torque coefficient (N/A)	0.97	0.97

2.3 Estimation of fuel consumption of GV and EV

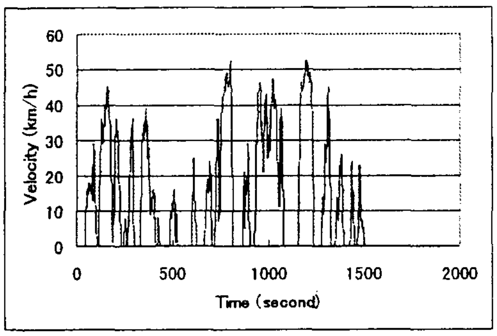
This section deals with electric power or fuel consumption for EV and GV in typical driving modes. As far as driving modes are concerned, we adopt a constant velocity of 40 km/h and actual driving patterns in the Tokyo area. In particular, the actual driving patterns include ten kinds of actual driving data as measured in Tokyo, whereby the average velocities are ranged between 4.62 km/h and 44.34 km/h [4].



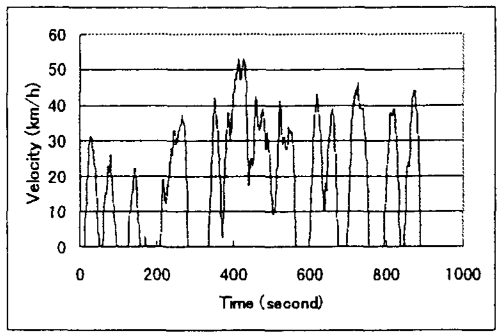
a) **Mode 1 : 4.62 km/h**



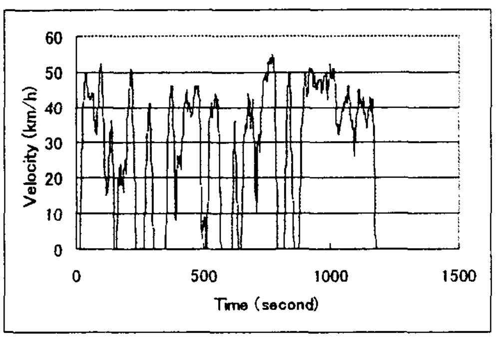
b) **Mode 2 : 8.35 km/h**



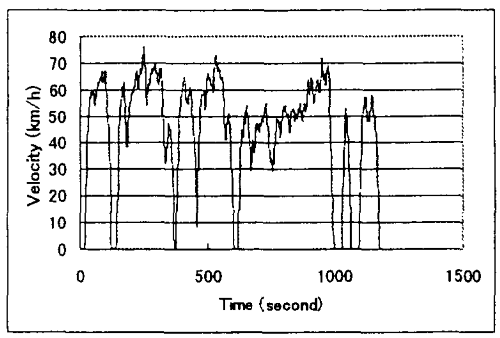
c) **Mode 3 : 14.63 km/h**



d) **Mode 4 : 18.47 km/h**



e) **Mode 5 : 28.50 km/h**



f) **Mode 6 : 44.34 km/h**

Values under the figures imply average velocities in corresponding driving modes

Fig. 1: Six representatives of ten actual driving modes measured in the Tokyo area [4]

Fig. 1 a to f depict six representatives of the ten modes, which cover situations of heavy traffic congestion as well as smooth traffic flows. Simulations based on this data enable us to evaluate the performances of the vehicles in actual traffic situations including serious congestion as well as smooth flow.

With regard to EV, efficiencies of charging and discharging batteries are also taken into consideration.

Table 4 and Table 5 show estimated energy consumption and cruising distance per charge under each driving mode.

Table 5 shows that cruising distances at constant speed more than doubles the range in the actual driving modes. The main reason is that the weights of EV are much heavier than the GV, leading to much more energy consumption when accelerating. On the other hand, energy to accelerate EV is not necessary in constant velocity, which leads to much longer cruising distances than in the actual driving modes.

Since the estimated variables are end-use energy consumption, it is necessary to input these variables into vector f so as to estimate life cycle resource consumption and environmental emissions by Equations (7) and (8).

3 Estimation of Life Cycle CO_2 Emissions of EV and GV

3.1 CO_2 emissions resulting from driving EV or GV

Based on the results of driving simulation, life cycle CO_2 emissions of EV and GV are estimated in this chapter. We put the estimated end-use energy consumption into vector f,

Table 4: Estimated results of energy consumption at different velocities

Driving modes	Average velocity km/h	GV [MJ/km]	GV [L/km]	EV Lead storage battery [MJ/km]	EV Lithium ion battery [MJ/km]
Actual	4.62	13.3	0.378	2.61	1.96
	8.35	7.81	0.222	2.29	1.71
	11.66	5.84	0.166	1.80	1.35
	14.63	4.82	0.137	1.55	1.16
	17.96	4.05	0.115	1.67	1.25
	18.47	3.96	0.113	1.80	1.34
	23.65	3.24	0.0922	1.42	1.06
	28.50	2.76	0.0787	1.36	1.01
	34.73	2.35	0.0669	1.13	0.85
	44.34	1.88	0.0536	0.84	0.63
Constant	40.00	1.96	0.0557	0.36	0.28

Table 5: Estimated cruising distances per charge of batteries under different driving patterns

Driving modes	Average velocity km/h	Cruising distance Lead storage km	Cruising distance Lithium ion km
Actual	4.62	37.22	83.57
	8.35	42.50	95.79
	11.66	54.02	121.44
	14.63	62.57	140.58
	17.96	58.27	131.35
	18.47	54.13	122.23
	23.65	68.50	154.12
	28.50	71.64	161.57
	34.73	86.08	193.49
	44.34	116.04	259.46
Constant	40.00	266.89	576.11

assuming that the annual driving distance is ten thousand kilometers. As a result, Fig. 2 shows relationships between annual CO_2 emissions and average velocities of the actual driving patterns.

As far as GV is concerned, burning gasoline occupies the largest share of CO_2 emissions, although oil refinery processes and some other processes also lead to emissions. As far as EV is concerned, most CO_2 is emitted in fossil-fueled power stations. Fig. 2 shows the apparent tendency that CO_2 generally decreases by increasing average velocities, although it also includes exceptional cases at 14.6 km/h and 18.5 km/h. These exceptional cases are caused by the actual driving modes adopted here [4].

Fig. 2 also shows that CO_2 emissions decrease in the order of GV, EV with lead storage batteries, and EV with lithium-ion batteries. At the same time, the difference between GV and EV are larger at lower average velocities. This is caused by the unique advantages of EV, so that idling is not necessary when it is stopped, and because of the fact that energy can be recovered and stored in the batteries when it is decelerating.

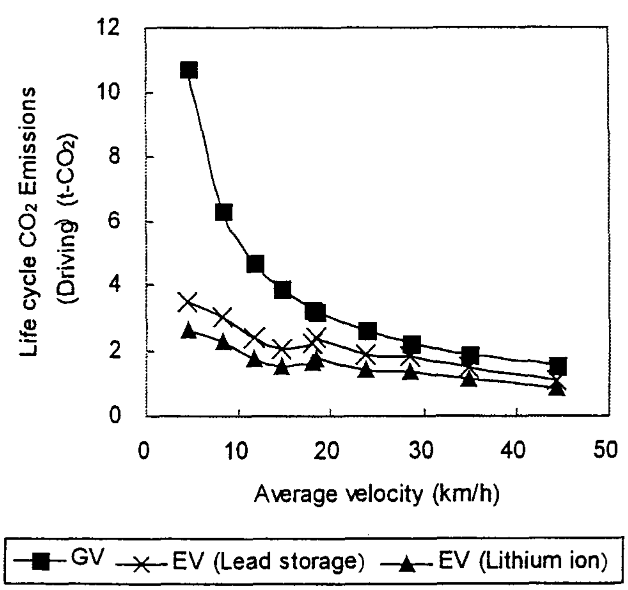


Fig. 2: Estimated annual CO_2 emission from driving vehicles in different velocities

3.2 CO_2 emissions resulting from manufacturing EV and GV

This section deals with an estimation of CO_2 emissions resulting from manufacturing EV and GV. The parts of EV are classified into a motor, batteries and other parts, including the chassis. As far as manufacturing of a motor and batteries are concerned, data was acquired by questionnaires to the maker of these products. **Tables 6, 7 and 8** show the data of principal component materials of the batteries and the motor. We input this data into corresponding items in f of the input-output table so that life cycle inventories are generated from Equations (7) and (8).

Table 6: Principal materials of the motor to drive EV

Parts of the motor	Materials	kg	%
Iron core	Silicon steel	22.0	50
Electric cable	Copper	3.0	7.0
Magnet	Nb-Fe-B	1.5	3.0
Shaft	Carbon steel	5.0	11
Flame bracket	Aluminum	11.5	26
Encoder and bearings	Steel	1.0	2.0
Total	–	44.0	100

Table 7: Principal materials of the lead storage battery (one unit)

Parts of the battery	Materials	kg	%
Anode	Lead	1.4	9.0
Active material (anode)	Lead dioxide	2.6	16
Cathode	Lead	1.1	7.0
Active material (cathode)	Lead	2.6	16
Separator	Polyethylene	0.3	2.0
Connecting conductor	Lead	1.0	6.0
Electrolytic bath	Polypropylene	0.8	5.0
Electrolytic solution	Sulfuric acid (35%)	6.2	39
Total	–	16.0	100

Table 8: Principal materials of the lithium ion battery (one unit)

Parts of the battery	Materials	kg	%
Anode	Aluminum	0.14	7.0
Active material (anode)	$LiNiO_2$	0.72	38
Cathode	Copper	0.26	14
Active material (cathode)	Hard carbon	0.31	16
Separator	Polyethylene	0.11	6.0
Electrolytic bath	Polyethylene	0.02	1.0
	Aluminum	0.14	7.0
Electrolytic solution	$LiPF_6$	0.02	1.0
	Propylene-carbonate (50%)	0.08	4.0
	Ethyl-methyl-carbonate (50%)	0.08	4.0
Total	–	1.88	100

As far as other parts, including the chassis of EV and GV, are concerned, there are corresponding items in the input-output table. Therefore, this data can be the direct input into the corresponding items in f so as to generate life cycle inventories.

Based on this data, we estimate CO_2 emissions from manufacturing EV with lead storage batteries and with lithium ion batteries. CO_2 emissions from manufacturing the lead storage batteries, the lithium ion batteries, the motor and the other parts of EV are estimated to be 853 kg, 1360 kg, 151 kg and 3670 kg, respectively. On the other hand, CO_2 emissions from manufacturing GV are estimated to be 4580 kg.

The **lifetime of batteries** is evaluated based on Equation (14):

(Lifetime) =
(Cruising distance per charging batteries) ×
(Average depth of charge and discharge) ×
(Lifetime number of charge and discharge) ÷
(Average annual driving distance) (14)

In Equation (14), the lifetime number of charge and discharge is assumed to be 358 and 500 for lead storage and lithium ion batteries, respectively, as attained from questionnaires given to the battery makers. The average annual driving distance is assumed to be 10,000 km. The average depth of charge and discharge is assumed to be 0.7. Thus, the evaluated lifetime depends upon the cruising distance per charging batteries in each driving mode. On the other hand, the lifetime of the chassis, motors and other parts is assumed to be a constant value of 9.5 years [5].

3.3 Life cycle CO_2 emissions integrating driving and manufacturing EV or GV

This section deals with an integration of the above-mentioned results on life cycle CO_2 emissions both from manufacturing and from driving. **Fig. 3** shows the relationships between the evaluated life cycle CO_2 emissions and average velocities. **Fig. 4** shows the share of manufacture and drive in life cycle CO_2 emissions of EV.

These results imply the following conclusions. First of all, life cycle CO_2 emissions of EV are less than GV. Next, the differences of life cycle CO_2 emissions become smaller, as average velocities increase. Thus, the relative superiority of EV over GV on CO_2 emissions increases in large cities with serious traffic congestion. In other words, the mitigation of traffic congestion is a useful measure to decrease CO_2 emissions as well as the introduction of EV.

According to the USCAR LCI of a generic vehicle [6], the share of manufacturing is between 10% and 20%. On the other hand, Fig. 4 indicates a larger share for manufactur-

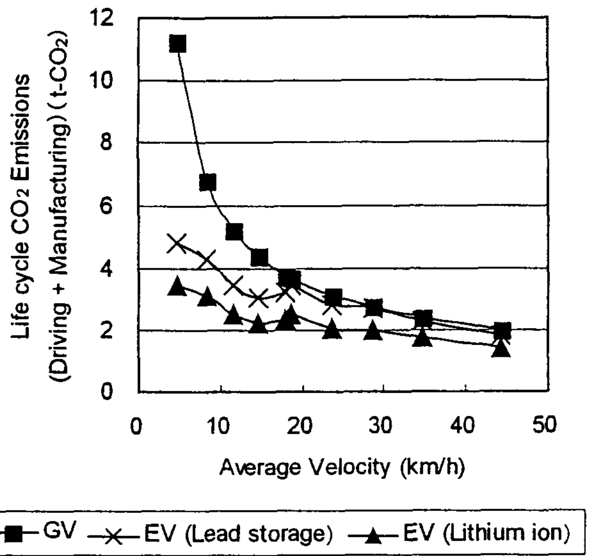


Fig. 3: Estimated sum of annual CO_2 emission from manufacturing and driving vehicles at different velocities

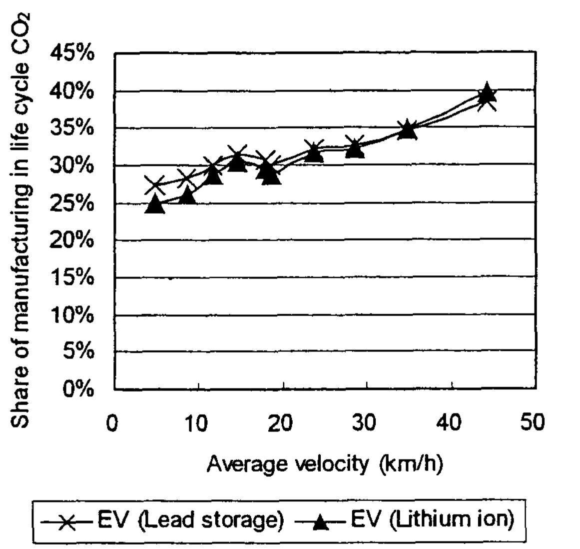


Fig. 4: Estimated share of manufacturing EV in life cycle CO_2 emission

ing than in the above literature. The following grounds are raised as reasons:

- The share of manufacturing tends to be larger than that estimated by bottom-up-LCA, since EIO-LCA includes an infinite number of repercussions.
- Driving the EV results in less CO_2 emissions than the GV, while manufacturing the EV leads to more CO_2 emissions than the GV, mainly due to the batteries. Consequently, the share of manufacturing becomes larger than in the above literature [6].

Since the share of manufacturing is considerably high in EV, careful attention should be paid to manufacturing batteries and other parts. Namely, an extension of the lifetime and improvements in the manufacturing processes are also effective measures to decrease life cycle CO_2 emissions from EV.

4 Conclusions

This article deals with the novel framework of LCA based on our novel mathematical tool, the Process-relational model. Then EV and GV were adopted as targets of this LCA methodology. Life cycle CO_2 emissions of these vehicles are estimated, including manufacture and use phase. Evaluated results quantified the differences of the life cycle CO_2 emissions in various driving modes from the evaluated results. The results also clarified the directions for research and development of EV and GV to decrease the emissions. We will further establish the LCA methodology and promote life cycle evaluation of other innovative technologies in the future.

The estimation in this study is not an LCA according to ISO14040s. So as to be in line with ISO 14040s, they need more comprehensive structures including a definition of goal and scope, inventory analysis, impact assessment and interpretation of results.

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